Echocardiography: An Overview

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In the past 25 to 30 years echocardiography has become a basic examination in clinical cardiology. Thus, it is becoming increasingly necessary for clinicians to be able to utilize it intelligently. Like all medical procedures echocardiography has advantages and limitations, and physicians need to know both. Some of the limitations are being minimized with advances in examination techniques and instrumentation, but many still exist. One limitation is that the ability to satisfactorily educate and train persons in the various ultrasonic techniques has not kept pace with the worldwide popularity of the examination. As a result, quality control will remain a problem at least in the immediate future. New developments in echocardiography as invasive and noninvasive tools are exciting and indicate that ultrasonic examination of the heart should play an increasingly important role in clinical cardiology.

History of Echocardiography

Echocardiography has come a long way since investigators first considered examining the heart with ultrasound more than 30 years ago. Keidel (1) is credited with being the first investigator to examine the heart ultrasonically. He transmitted ultrasound through the chest and recorded those sound waves that arrived on the other side in much the same way as we use the conventional X ray. He was trying to calculate cardiac volumes using the technique of "through transmission" ultrasound. This ultrasonic approach was essentially abandoned, but interest in it has been renewed with the advent of computer technology. One can now obtain an ultrasonic image of the heart much as one obtains a computerized tomogram using X rays.

Echocardiography as we know it today is principally based on the detection of reflected ultrasound rather than "through transmission" ultrasound. The reflected technique is basically an adaptation of sonar used for detecting underwater objects and for nondestructive testing in industry. The first investigator to use reflected ultrasound to examine the heart was the physicist Helmuth Hertz, whose father was working for Siemens Corporation and had access to a commercial ultrasonoscope being used in industry. At the time many investigators were using similar instruments to examine various organs of the body. Hertz thought it would be interesting to examine the heart in this fashion and he convinced a cardiologist, Inge Edler, to examine the heart of some of his patients. This collaboration in Lund, Sweden, was probably the true beginning of echocardiography or "ultrasound cardiography," (2) as it was then called. Other investigators (3,4) in Europe began examining the heart with ultrasound soon thereafter. Although they noted several pathologic conditions and described many echoes from various parts of the heart, at that time echocardiography was principally applied to detecting mitral stenosis by assessing the diastolic E to F slope (5).

By the early 1960s European interest in echocardiography or ultrasound cardiography had essentially disappeared. No new investigators were involved and the productivity of the early workers decreased dramatically. Soon thereafter a few investigators in the United States began to experiment with the technique of reflective ultrasound to examine the heart (6–8). The commercial instruments available were built primarily to examine the midline of the brain, which was then the principal diagnostic application of ultrasound. The display was the "A-mode" presentation whereby the reflected echo appeared as a spike on the oscilloscope. Any echo caused by a moving structure of the heart would be demonstrated as a moving spike on the oscilloscope. To better record the motion, the "A-mode" or spike was converted to a bright dot or "B-mode." The oscilloscope was then swept to introduce time. This "slow sweep" or "M-mode" then became the standard method of recording ultrasonic images of the heart.

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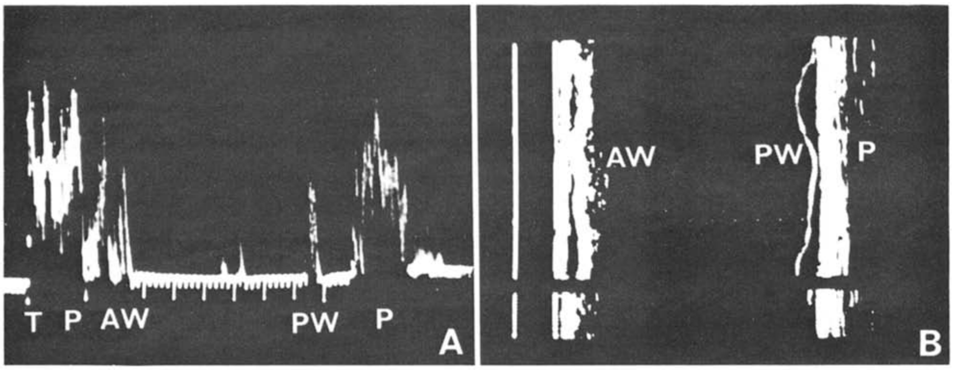
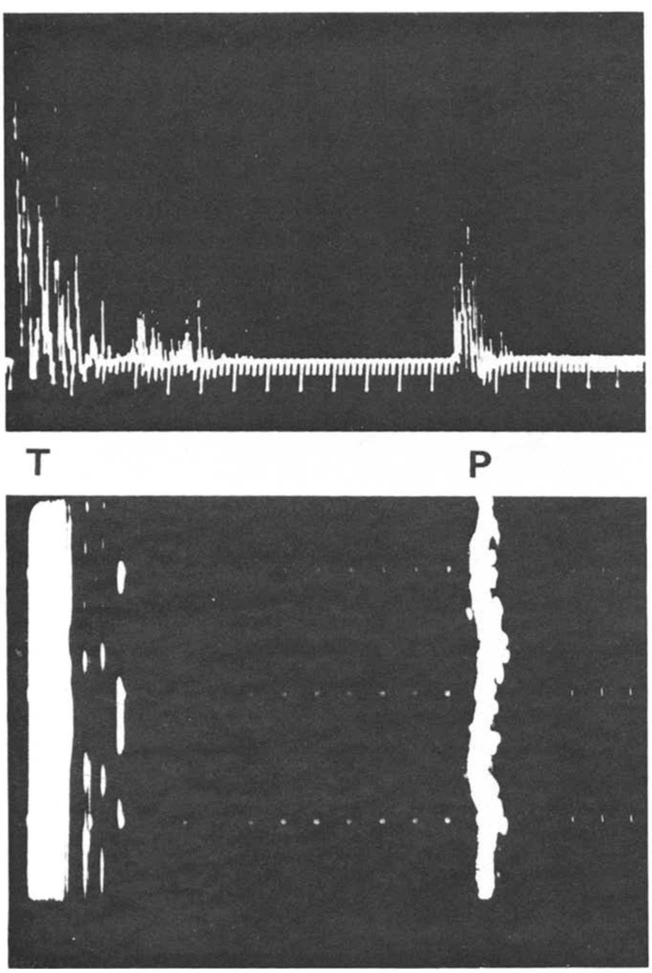


Figure 1. Echocardiograms taken in the early 1960s of a patient with pericardial effusion. AW = anterior wall; P = pericardium; PW = posterior wall; T = transducer. (Reprinted from Feigenbaum H, Zaky A, Waldhausen JA [15], with permission.)

Figure 2. An ultrasonic recording from a patient with a dilated heart but no pericardial effusion. This early echocardiogram merely recorded a strong echo from the vicinity of the posterior left ventricular wall (P). The fact that this echo was single differentiated this recording from Figure 1, which represented pericardial effusion. T = transducer. (Reprinted from Feigenbaum H, Zaky A, Waldhausen JA [15], with permission.)



Development of M-mode technique. The early echocardiographs were insensitive and the sources of many of the ultrasonic signals were poorly understood. For these reasons, only echoes from strong reflective interfaces, such as the anterior mitral leaflet and the posterior wall of the heart, were recorded. The technique that generated some interest in the United States was that used to detect pericardial effusion (8). Figure 1 shows an echocardiogram, obtained in the 1960s, from a patient with pericardial effusion. On the A-mode oscilloscope, the echo labeled PW was moving with cardiac action. The motion was better displayed on the "slow sweep" or "M-mode" (Fig. 1B). Figure 2, another early echocardiogram, indicates how one identified a patient with a dilated heart and no pericardial effusion. In this study a single, poorly moving echo is noted in the vicinity of the posterior wall of the heart.

From these early beginnings, echocardiography made steady progress. First, the number of investigators showing an interest in echocardiography began to grow, slowly at first, then rapidly during the late 1960s and early 1970s. Second, more parts of the heart were recognized echocardiographically. The discovery was made that an intracardiac injection of almost any liquid would produce a cloud of echoes that could be recorded echocardiographically, and thus contrast echocardiography was developed. This technique immensely increased our ability to identify what we were seeing on the echocardiogram (9). As a result, we were able to improve our examining techniques. We fearlessly began increasing the gain and recording echoes that now had some clinical meaning. Last, there was an obvious dramatic improvement in instrumentation. Both investigative physical scientists and commercial companies began to concentrate more effort on the development of better echocardiographic instruments once interest began to grow. With the advent of strip chart recorders, the M-mode echocardiogram quickly evolved into a tracing such as that shown in Figure 3. We learned how to move the ultrasonic beam or to create an M-mode scan so as to record the various parts of the heart on one recording. Thus, as the instruments improved, new examining techniques were developed, the

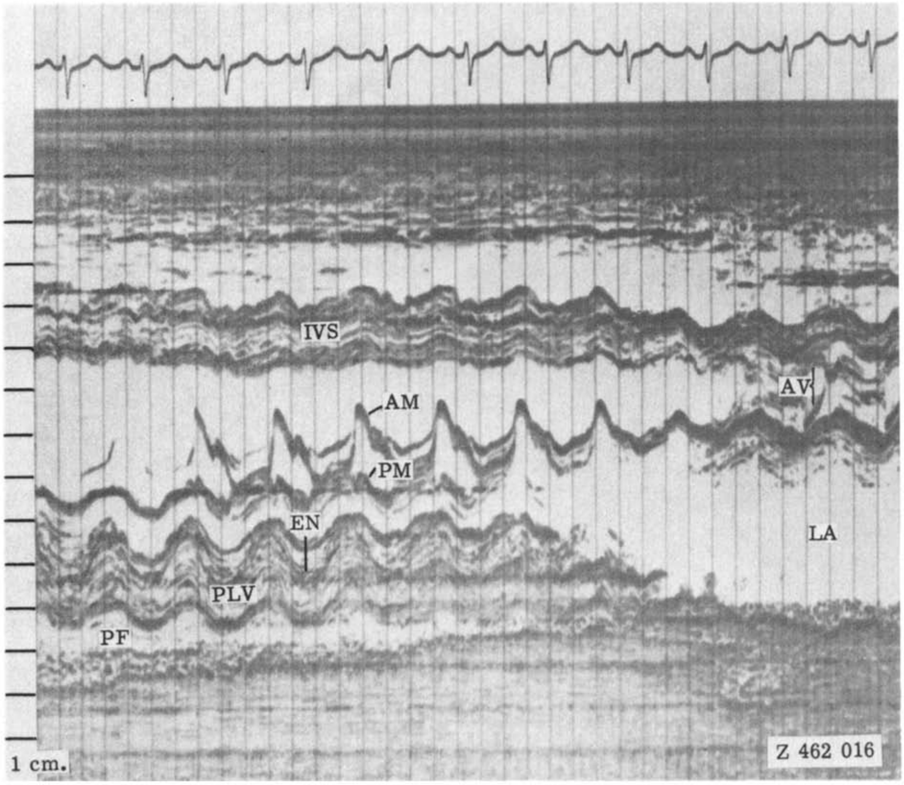
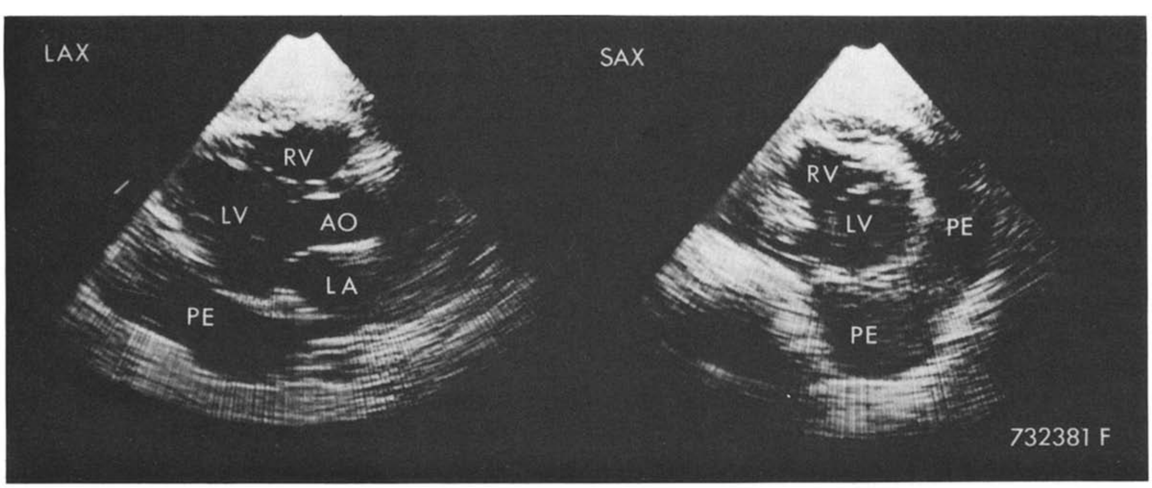


Figure 3. M-mode scan of a patient with pericardial effusion recorded on a strip chart recorder. AM = anterior mitral leaflet; AV = aortic valve; EN = posterior left ventricular endocardium; IVS = interventricular septum; LA = left atrium; PF = pericardial fluid; PLV = posterior left ventricular wall; PM = posterior mitral leaflet. (Reprinted from Feigenbaum H [10], with permission.)

recordings became better and the amount of clinically useful information increased.

Development of two-dimensional techniques. The development that drastically changed echocardiography was two-dimensional echocardiography, sometimes called "real-time" or "cross-sectional" echocardiography (11,12). By rapidly moving the ultrasonic beam using either a mechanical (12,13) or an electronic, phased array (14) system, one can obtain slices or tomograms of the heart using ultrasound. Figure 4 demonstrates how echocardiographic detection of pericardial effusion improved with the two-dimensional technique. The distribution and quantity of the fluid can be better appreciated using this spatially oriented tool. More dramatic evidence of the evolution of echocardiography can be found in a comparison of Figures 2 and 5. Both recordings

Figure 4. Two-dimensional echocardiogram of a patient with a large pericardial effusion. The long axis (LAX) and short axis (SAX) views permit an excellent assessment of the size and distribution of the pericardial effusion (PE). AO = aorta; LA = left atrium; LV = left ventricle; RV = right ventricle. (Reprinted from Feigenbaum H [10], with permission.)



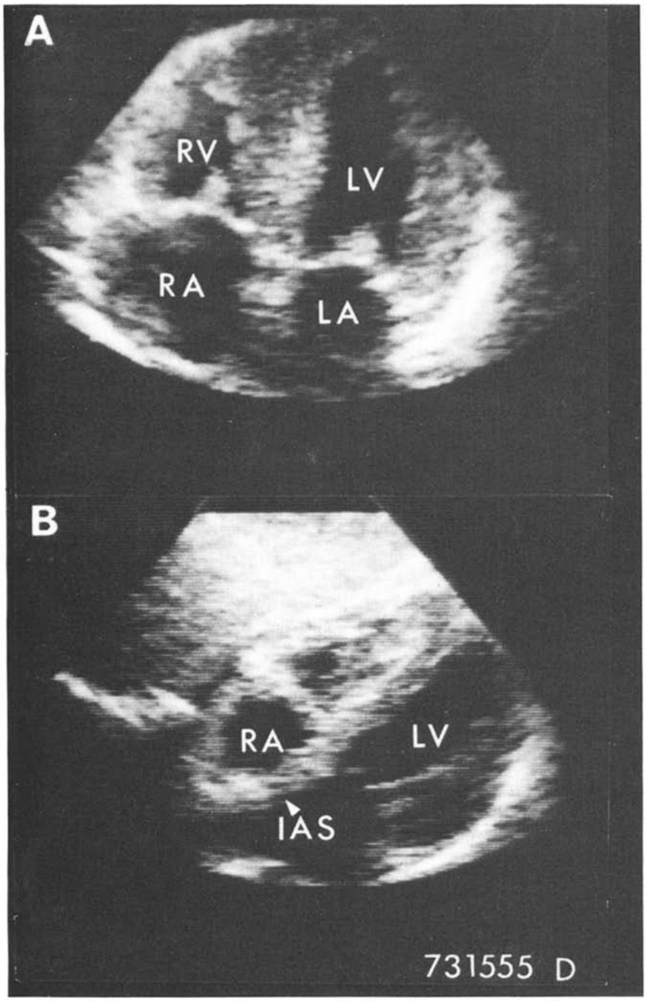


Figure 5. Four chamber (**A**) and subcostal (**B**) two-dimensional echocardiograms of a patient with hereditary amyloidosis. The four chamber view demonstrates the markedly thickened walls and valves. There is also thickening of the interatrial septum (IAS) noted on the subcostal examination. The cardiac walls have a "stippled" appearance which may be characteristic of an infiltrative cardiomyopathy. (Reprinted from Feigenbaum H [10], with permission.)

are from patients with primary myocardial disease. In the early 1960s (Fig. 2) we were satisfied when an echo from the back wall of the heart suggested that the wall was not moving very well and was a large distance from the transducer (15). Nearly 20 years later (Fig. 5) we have a detailed spatially correct recording of the heart. In this recording from a patient with amyloid heart disease one can appreciate the thickness of the walls, the size of the chambers and the thickened valve leaflets and septa. In addition, one can detect some stippling of the myocardial echoes, which is compatible with the infiltrative cardiomyopathy of this patient.

Development of Doppler recording technique. The history of echocardiography is not limited to M-mode and two-dimensional techniques. A concurrent history exists for the Doppler technique of obtaining ultrasonic information from circulating blood. In the mid 1960s, investigators began using the Doppler technique to detect occlusive disease in the peripheral vessels (16–18). This technique utilized relatively inexpensive ultrasonic devices using continuous wave ultrasound, and this basic approach has remained virtually intact over the years. Continuous wave Doppler recording is a key technique in the noninvasive analysis of peripheral artery disease. Several investigators have also used it to examine the heart (19–21). With it, one could detect changes in the velocity of blood flow within the heart in patients with valvular heart disease. One also could record from the thoracic aorta a Doppler signal that provided information concerning hypertrophic obstructive cardiomyopathy, aortic regurgitation and other conditions (22,23). In addition, investigators have tried to use the Doppler technique to measure flow within the aorta and possibly cardiac output (24,25).

Combined Doppler and echocardiographic techniques. The two histories of echocardiography merged with the development of pulsed Doppler recording (26). By pulsing the Doppler transducer, it became possible both to record the Doppler signal and to create a reflected image using M-mode or two-dimensional echocardiography. With the advent of combined Doppler examinations and ultrasonic imaging, investigators began exploring the blood flow patterns within the heart and great vessels (27–29). Pulsed Doppler recording is still in the relatively early stages of development. Its clinical utility is gradually increasing and the technique is under intense investigation. As one might expect, the Doppler examination is proving to be valuable for the detection of intracardiac shunts (30), and has thus been more popular among pediatric echocardiographers than in the adult cardiology laboratories.

Current Status of Echocardiography

To one who has lived and worked through most of the history of echocardiography, the current worldwide acceptance of this diagnostic tool is indeed gratifying. The various echocardiographic examinations now play an important role in almost every aspect of clinical cardiology. The table of contents of a textbook on echocardiography is almost identical to that of a textbook on clinical cardiology. In many clinical situations, such as valvular heart disease, congenital heart disease, cardiomyopathies, pericardial effusion and intracardiac masses, echocardiography is the procedure of choice for making a definitive diagnosis. In other situations, the echocardiographic information may be indirect and less specific but may add significantly to the overall clinical picture and the management of the individual patient.

Advantages. There are many obvious reasons for the popularity and general acceptance of echocardiography. First, it is a truly noninvasive approach and, except for contrast echocardiography, does not even require an intravenous injection. The examination is completely painless and thus has excellent patient acceptance. To the best of our knowledge, the biologic effects of ultrasound at the energy levels used for diagnostic purposes are extremely small and no untoward reaction has ever been reported with routine diagnostic echocardiography. Thus, the examination appears to be extremely safe and avoids even the minimal hazard of ionizing radiation. Another advantage is that in these days of great concern about rising medical costs, echocardiography is less expensive than the various other new, sophisticated imaging techniques. Its cost is roughly half that of any nuclear imaging study and approximately one-tenth the cost of any invasive angiographic examination. The ultrasonic technique will undoubtedly continue to be less costly than any of the newer examinations, such as digital vascular imaging, positron emission tomography, nuclear magnetic resonance or cardiac imaging with computer tomography.

Clinical application. The widespread popularity of echocardiography makes it vitally important for all clinicians treating patients with heart disease to have a good understanding of what echocardiography can and cannot do. Because echocardiography was only recently introduced into educational programs, most practicing clinicians did not study the technique during their formal training and have had no firsthand experience with it. Under these circumstances, the examination can be both underutilized and overutilized. Some older physicians who recall many previously heralded but disappointing diagnostic techniques, such as ballistocardiography and to some extent vectorcardiography, remain skeptical of new examinations, including echocardiography. They will probably not learn enough about echocardiography to become comfortable with it and thus will never utilize it in its most efficient manner. Other physicians will use it incorrectly as a screening tool for all patients with known or suspected heart disease. Many noncardiologists will mistakenly order an echocardiogram in lieu of a cardiology consultation.

The improper use of echocardiography can be very expensive from the point of view of both patient management and overall medical costs. Physicians who underutilize echocardiography may needlessly subject their patients to more costly, more hazardous examinations. Or they may miss an important cardiac diagnosis and thus mismanage the patient. Physicians who overutilize the examination may unnecessarily contribute to rising medical costs.

Although most echocardiographic laboratories are in hospitals, the technique is an ideal outpatient test. In fact, as the instruments become smaller and less expensive, one can anticipate that more echocardiograms will be performed in physicians' offices. This approach should result in increased efficiency. Unfortunately, because the current medical reimbursement system pays preferentially for procedures and tests, there will be a tremendous temptation to overuse the examination once the echocardiographs are in doctors' offices. If such abuse occurs, we will all suffer the consequences.

Limitations of Echocardiography

Educational problems. Echocardiography has many well recognized limitations. Ultrasound does not travel well through bone or air-containing lung; thus the examination must be performed with some skill to avoid those areas of the chest that will not permit adequate imaging of the heart. This requirement poses two problems. First, the examination requires training and expertise. As echocardiography has grown into a fairly sophisticated and somewhat complicated examination, the period of training required to become competent in its performance is lengthening. Ten to fifteen years ago one could probably learn all that there was to know about echocardiography in a few weeks. Now it is doubtful that one could accomplish this task in a few months.

The American Society of Echocardiography has devised guidelines for training both physicians and technicians in echocardiography. These guidelines are not an obstacle to the physician who is still in formal training and wishes to become proficient in echocardiography. He or she merely needs to make certain that the training institution can provide the educational requirements. However, there are problems for the physician who is already in practice and now wishes to become proficient in performing and interpreting echocardiograms. Ideally this person should interrupt his or her practice or medical career to spend time at an institution that will give personalized instruction in echocardiography. Unfortunately, this approach is not very practical. It is difficult for physicians to leave a practice for any significant length of time. In addition, relatively few institutions will provide the necessary instruction. In fact, physicians in practice usually take a short postgraduate course in echocardiography or visit a laboratory for a few days and then immediately begin examining patients. Those who are conscientious and serious about the examination will take 6 months to a year practicing their newly learned techniques and checking their results with other available tests to improve their competence in the examination. Once confident that they are proficient, they work with a technologist to establish a well working laboratory. Unfortunately, this approach is probably the exception rather than the rule. Because physicians are more involved in echocardiographic interpretation than in the actual examination, it is doubtful that many of them will take the time to learn to perform it proficiently. They will merely hire, as soon as possible, a technician who will essentially run the laboratory.

With the obvious diversity in training and experience among physicians and technicians working with echocardiography, and with the lack of any available means of demonstrating a person's proficiency with the examination, it is no wonder that the quality of echocardiography varies dramatically. The more knowledgeable a physician is about echocardiography, the more likely he or she will be able to judge the quality of the echocardiography being performed on his or her patients.

Technical problems. The technical limitations not only have created an educational problem for echocardiography, but also have created a situation whereby some patients are difficult to examine echocardiographically, irrespective of the expertise of the examiner. Fortunately, because both the equipment and the skill of the examiners are improving, the number of patients who cannot be examined echocardiographically is becoming very small. Even patients with coronary artery disease, barrel chest and emphysema can be studied; techniques have been devised for gaining clinically useful information in almost all of these patients. Naturally, the quality of the study will still vary. In some patients, we may be able to answer the clinical question even though the quality of the image may not be very good. In others, we may be able to make the qualitative diagnosis, but the image may not be adequate to make a quantitative diagnosis. Thus, although our techniques and instruments are improving, there are still technical limitations in the quality of the recording in individual patients.

The limitations of echocardiography have been emphasized from its inception and must be appreciated by all who wish to utilize it. However, all tests have specific limitations, and those of echocardiography are not necessarily greater than those of any other cardiologic examination. One must be aware of the specific limitations of tests just as one must know the side effects of drugs.

Future of Echocardiography

Some of the anticipated developments in echocardiography are exciting, and the overall future of the technique is very bright. Continued growth in the use of the ultrasonic examination is assured, even if no technologic breakthroughs are developed. As the instruments become smaller and less expensive, more of them will be located in physicians' offices. As more clinicians recognize the usefulness of echocardiography in patients with acute or suspected acute myocardial infarction, one can anticipate dedicated units in coronary care units and even emergency rooms. It is not inconceivable that in the near future coronary care unit nurses may be taught how to obtain echocardiograms so that they can perform the examination, especially in patients with a recurrent chest pain syndrome.

Exercise echocardiography. Echocardiography has been less often used than nuclear cardiology for quantitation and stress testing. With recent developments in both instrumentation and examination techniques, echocardiography is making great strides in both areas. Although it is still quite difficult to obtain satisfactory echocardiograms in the exercising subject, several investigators (31,32) have noted that it is possible to obtain high quality echocardiograms in the immediate postexercise period in almost all patients. This finding means that patients can be given a standard treadmill exercise test that is preceded and followed immediately by a two-dimensional echocardiographic examination to detect any changes in regional wall motion. This development should have many practical advantages. First, there should be some cost saving because echocardiography is less expensive than nuclear studies. Second, some areas of the heart are examined better with echocardiography than with isotope techniques. The ultrasonic examination permits beat to beat images of many cardiac cycles from multiple views using inherently better resolution (33). Last, as echocardiographic equipment starts to move into the physician's office where a treadmill already exists, the combination of the two examinations is a logical next step.

Quantitation of measurements. Although M-mode echocardiography has been a quantitative examination since investigators first measured the mitral valve E to F slope, quantitation of two-dimensional echocardiography evolved more slowly. The delay occurred partly because of the difficulty in measuring information presented in a videotape format. With the advent of newer videotape and video disk recorders, the handling of data on videotape is becoming easier. Electronic calipers are now making measurements convenient. Examinations are becoming more standardized so that reproducibility can be acceptable for various measurements. As the explosion in technology in the videotape and computer fields continues, one can anticipate significant improvement in the ability to quantitate and analyze the ultrasonic examination obtained in a video format.

Improvements in instrumentation. There is every reason to believe that many more improvements in instrumentation will come. The marketplace is encouraging more companies to use their ingenuity to develop better instruments. The signal to noise ratio is already significantly better. Many of the technical problems in patients with more difficult conditions are being solved with better instruments and better transducer design. Digital processing of the ultrasonic image is already being done by several commercial companies. Improved gray scale is also a part of many of the newer instruments. With better signal to noise ratios and better penetration we are able to use transducers with higher frequencies, which inherently have better resolution. In the early days of echocardiography a 2 to 2.25 MHz transducer was the standard frequency for adult patients, and on occasion even a 1.75 MHz transducer was necessary to penetrate the chest. Most commercial echocardiographs now use 3 to 3.5 MHz transducers for the standard adult examination.

Invasive echocardiography. Echocardiography need not be solely a noninvasive examination. Several investigators (34,35) have experimented with intraesophageal echocardiographic techniques. Transducers can easily be placed on esophageal catheters or on endoscopic instruments. This approach to examining the heart ultrasonically has some advantages because there is no interference by the chest wall structures. Such an examination could prove most useful in the intraoperative or postoperative patient (36,37) or during exercise. Direct ultrasonic examination at the time of surgery will undoubtedly be performed with increasing frequency. Preliminary reports (38) of using an ultrasonic probe directly on the surface of the heart during surgery have already been made. Excellent images of the coronary arteries are possible with this technique. By utilizing a very high frequency transducer, one can obtain sufficient detail to result in an almost histologic diagnosis. This surgical approach could prove ideal for exploring abnormalities within coronary vessels before bypass grafting is performed. One could also use the ultrasonic transducer to explore the heart before or after surgical correction of a valvular or congenital abnormality. In another invasive approach, one could place the transducer on a catheter (39,40). Again, one could use a very high frequency transducer and obtain a recording that is of almost histologic value.

Echocardiography for tissue diagnoses. The use of ultrasound to make tissue diagnoses has been studied for many years (41). There are many theoretical reasons why ultrasound is appropriate to provide this type of information. Clinical echocardiography is already used for some tissue identification. Calcified structures are readily identified using echocardiography. Fibrosis is easily differentiated from normal cardiac tissue. Scarred myocardium secondary to myocardial infarction has a different appearance from that of nonscarred but ischemic muscle (42). Preliminary observations indicate that certain forms of cardiomyopathy, hypertrophic or infiltrative, may produce a characteristic stippled appearance of the myocardium (Fig. 5) (43–45). Many animal studies (46,47) have demonstrated reproducible acoustic changes with myocardial infarction. Conversion of the gray scale image to color has been performed and is commercially available (48). The color enhances the differences in the returning echoes and permits better identification of tissue types. All of these findings support the possibility of using echocardiography for tissue identification.

Three-dimensional echocardiography. Echocardiography started with the M-mode technique, which is basically a one-dimensional examination, the second dimension being time. Advances were made with the introduction of two-dimensional echocardiography. A logical next step would be the development of three-dimensional echocardiography. Many approaches for creating three-dimensional echocardiography have been proposed (49–51). All of the techniques to date have utilized composite two-dimensional echocardiograms whereby the position of the transducer in space is known and the various two-dimensional images are reconstructed. This approach is now fairly tedious and complicated. With advances in computer technology and analysis of individual echocardiographic tomograms, this technique may develop dramatically. There is at least a theoretical possibility that one could obtain a real-time three-dimensional echocardiogram. Such an approach would have many technical difficulties in obtaining and recording the data and in displaying the real-time three-dimensional image. However, there are no theoretical limitations to this type of examination and the resultant cardiac images could be spectacular.

Doppler echocardiography. There is every reason to expect continuing advances in Doppler echocardiography (52). The introduction of the fast Fourier transform analysis has become a major advance in analysis of the Doppler signal. The combination of the Doppler technique with two-dimensional echocardiography has also improved the prospect of quantitating the flow within the heart and great vessels (53). Multigate Doppler recording provides an opportunity to actually map blood flow within the heart superimposed on an M-mode or two-dimensional image (54). Preliminary data indicate that this approach is a useful way of recording Doppler signal information in patients with a cardiac shunt (55).

Contrast echocardiography. This is another exciting technique that holds great promise. The method utilizes an intravascular injection of a liquid containing tiny microbubbles that in turn produce a cloud of echoes on the echocardiogram. Almost any liquid contains suspended microbubbles and will produce such an effect when injected. Initially this technique was used to help identify the various intracardiac structures and resultant echoes (56). Since then, it has been most useful in detecting right to left shunts (57). It has also been valuable in identifying tricuspid regurgitation (58) and, to a lesser degree, left to right shunts (59). Some investigators have used contrast echocardiography in the cardiac catheterization laboratory to obviate the need for cineangiography, especially in the young, critically ill patient (60).

The contrast agents used most frequently are saline solution or indocyanine green dye. The latter substance has a very low surface tension so that small bubbles stay suspended longer. New contrast agents have been introduced. Manufactured bubbles using either gelatin or saccharide have been used experimentally (61). These contrast agents are extremely echogenic and have many potential applications. One advantage is that the number of bubbles introduced is known, presenting the prospect of using contrast echocardiography in a more quantitative fashion. In addition, the quality of the contrast studies is more uniform and the examinations are of better quality. Injection of the new contrast agents in the root of the aorta or in the coronary arteries can yield excellent images of the myocardium and provides a means of assessing myocardial perfusion (62). There has been interest in the use of hydrogen peroxide as a contrast-producing agent. The substance was first used for this pur-

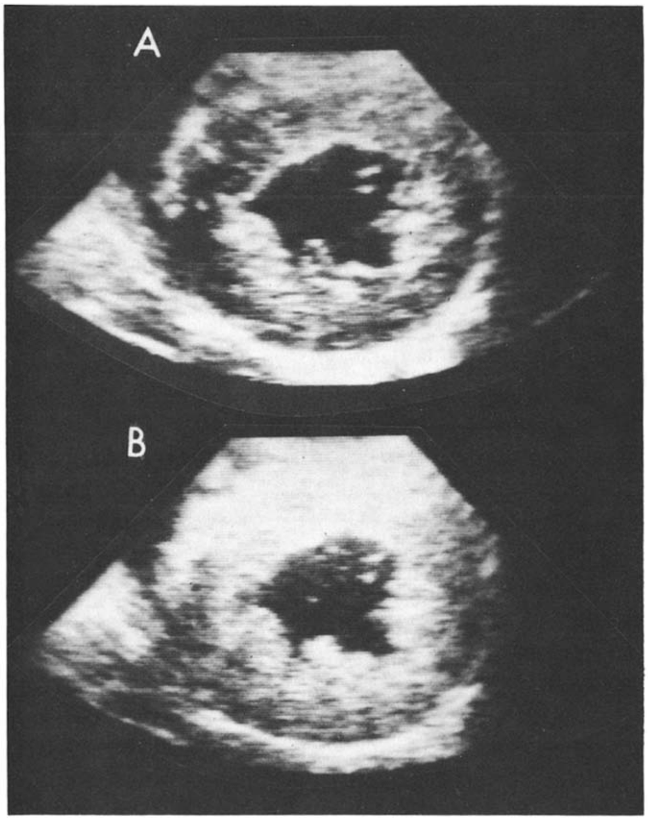


Figure 6. Short axis two-dimensional echocardiograms of the left ventricle of a dog before **(A)** and after **(B)** injection of hydrogen peroxide in the root of the aorta. After the contrast injection, the left ventricular myocardium is filled with contrast-producing microbubbles allowing for an excellent assessment of myocardial perfusion.

pose by the Chinese (63) and more recently by investigators in the United States (64). Figure 6 demonstrates the contrast effect from an injection of hydrogen peroxide in the root of the aorta of a dog. This technique produces excellent visualization of myocardial perfusion.

There will undoubtedly be further research on various types of contrast-producing agents. Although there have been a few isolated reports showing contrast bubbles traversing the pulmonary vasculature (65,66), almost all of the substances described thus far do not pass through capillaries. The microbubbles are not small enough to traverse the capillaries. There are some theoretical ways by which one could produce contrast bubbles on the left side of the heart with a peripheral venous injection, but these techniques have yet to be demonstrated.

References

1. Keidel WD. Uber eine Methode zur Registrierung der Volumanderungen des Herzens am Menschen. Z Kreislaufforsch 1950:39:257–61.
2. Edler I, Hertz CH. Use of ultrasonic reflectoscope for continuous recording of movements of heart walls. Kungl Fysiogr Sallsk Lund Forhandl 1954:24:5–9.
3. Effert S, Erkens H, Grossebrockhoff F. Ultrasonic echo method in cardiological diagnosis. Germ Med Methods 1957:2:325–8.
4. Schmitt W, Braun H. Ultrasonic cardiography in mitral defect and in nonpathological heart. Z Kreislaufforsch 1960;49:214–22.
5. Edler I, Gustafson A. Ultrasonic cardiogram in mitral stenosis. Acta Med Scand 1957;159:85–90.
6. Wild JJ, Crawford HD, Reid JM. Visualization of the excised human heart by means of reflected ultrasound or echography. Am Heart J 1957;54:903–6.
7. Joyner CR, Reid JM, Bond JP. Reflected ultrasound in the assessment of mitral valve disease. Circulation 1963;27:503–11.
8. Feigenbaum H, Waldhausen JA, Hyde LP. Ultrasound diagnosis of pericardial effusion. JAMA 1965;191:711–4.
9. Gramiak R, Shah PM, Kramer DH. Ultrasound cardiography: contrast studies in anatomy and function. Radiology 1969:92:939–48.
10. Feigenbaum H. Echocardiography. 3rd ed. Philadelphia: Lea & Febiger, 1981:471,481,486.
11. Bom N, Lancee CT, Honkoop J, Hugenholtz PC. Ultrasonic viewer for cross-sectional analyses of moving cardiac structures. Int J Biomed Comput 1971:6:503–8.
12. Griffith JM, Henry WL. A sector scanner for real time two-dimensional echocardiography. Circulation 1974;49:1147–52.
13. Eggleton RC, Feigenbaum H, Johnston KW, Weyman AE, Dillon JC, Chang S. Visualization of cardiac dynamics with real-time B-mode ultrasonic scanner. In: White D, ed. Ultrasound in Medicine. New York: Plenum, 1975;1:385–93.
14. Kisslo J, VonRamm OT, Thurstone F. Cardiac imaging using a phased array ultrasound system. II. Clinical technique and application. Circulation 1976;53:262–7.
15. Feigenbaum H, Zaky A, Waldhausen JA. Use of ultrasound in the diagnosis of pericardial effusion. Ann Intern Med 1966:65:443–52.
16. Strandness DE, McCutcheon EP, Rushmer RF. Application of a transcutaneous Doppler flow meter in evaluation of occlusive arterial disease. Surg Gynecol Obstet 1966;122:1039–45.
17. Sigel B, Popley GL, Boland JP, Wagner DK, Mopp EM. Augmentation of flow sounds in the ultrasonic detection of venous abnormalities. Invest Radiol 1967;2:256–8.
18. Lavenson GS, Rich NM, Baugh JH. Value of ultrasonic flow detection in the management of peripheral vascular diseases. Am J Surg 1970;120:522–6.
19. Yoshida T, Mori M, Nimura Y, et al. Study on examining the heart with ultrasonics: III. Kinds of Doppler beats. Jpn Circ J 1956;20:228–35.
20. Kostis JB, Fleischmann D, Bellet S. Use of the ultrasonic Doppler method for the timing of valvular movement. Circulation 1969;40:197–207.
21. Kalmanson D, Veyrat C, Derai C, Savier CH, Berkman M, Chiche P. Non-invasive technique for diagnosing atrial septal defect and assessing shunt volume using directional Doppler ultrasound. Correlations with phasic flow velocity patterns of the shunt. Br Heart J 1972;34:981–91.
22. Thompson PD, Mennel RG, MacVaugh H, Joyner CR. The evaluation of aortic insufficiency in humans with a transcutaneous Doppler velocity probe (abstr). Ann Intern Med 1970;72:718.
23. Joyner CR Jr, Harrison FS Jr, Gruber JW. Diagnosis of hypertrophic subaortic stenosis with a Doppler velocity flow detector. Ann Intern Med 1971;74:692–6.
24. Light LH. Transcutaneous observation of blood velocity in the ascending aorta in man. Biol Cardiol 1969;26:214–6.
25. Huntsman LL, Gams E, Johnson CC, Fairbanks E. Transcutaneous determination of aortic blood flow velocities in man. Am Heart J 1975;89:605–12.
26. Johnson SL, Baker DW, Lute RA, Dodge HT. Doppler echocardiography: the localization of cardiac murmurs. Circulation 1973;48:810–22.

27. Kalmanson D, Veyrat C, Bouchareine F, Degroote A. Non-invasive recording of mitral valve flow velocity patterns using pulsed Doppler echocardiography. Application to diagnosis and evaluation of mitral valve disease. Br Heart J 1977;39:517–28.

28. Ward JM, Baker DW, Rubenstein SA, Johnson SL. Detection of aortic insufficiency by pulsed Doppler echocardiography. J Clin Ultrasound 1977;5:5–10.

29. Goldberg SJ, Areias JC, Spitaels SEC, deVilleneuve VH. Echo Doppler detection of pulmonary stenosis by time-interval histogram analysis. J Clin Ultrasound 1979;7:183–9.

30. Stevenson JG, Kawabori I, Dooley T, Guntheroth WG. Diagnosis of ventricular septal defect by pulsed Doppler echocardiography. Circulation 1978;58:322–6.

31. Maurer G, Nanda N. Two dimensional echocardiographic evaluation of exercise-induced left and right ventricular asynergy: correlation with thallium scanning. Am J Cardiol 1981;48:720–7.

32. Limacher MC, Quinones MA, Poliner LR, Waggoner AD, Nelson JG, Miller RR. Detection of coronary artery disease with exercise two-dimensional echocardiography: description of a clinically applicable and accurate method (abstr). Circulation 1981;64(suppl IV): IV-94.

33. Crawford MH, Amon KW, Vance WS, Sorensen SG, Rabinowittz AC. Advantage of two-dimensional echo over radionuclide angiography for detecting acute changes in LV performance during exercise (abstr). Circulation 1981;64(suppl IV):IV-13.

34. Frazin L, Talano JV, Stephanides L, Loeb HS, Kopel L, Gunnar RM. Esophageal echocardiography. Circulation 1976;54:102–8.

35. Hisanaga K, Hisanaga A, Nagata K, Ichie Y. Transesophageal cross-sectional echocardiography. Am Heart J 1980;100:605–9.

36. Matsumoto M, Oka Y, Strom J, et al. Application of transesophageal echocardiography to continuous intraoperative monitoring of left ventricular performance. Am J Cardiol 1980;46:95–105.

37. Kremer P, Schwartz L, Chahlan MK, Gutman J, Schiller NB. Intraoperative monitoring of left ventricular performance by transesophageal M-mode and 2-D echocardiography (abstr). Am J Cardiol 1982;49:956.

38. Sahn DJ, Brandt PWT, Barratt-Boyes B, et al. Ultrasonic (ultra)/angiographic (angio) correlation for imaging of coronary atherosclerotic lesions (Cal) in open chested humans during surgery (abstr). Circulation 1981;64(suppl IV):IV-205.

39. Stephens DD, Palacios IF, Block PC, Weyman AE. Intracardiac echocardiographic evaluation of phasic right atrial free wall dynamics (abstr). Circulation 1981;64(suppl IV):IV-128.

40. Glassman E, Kronzon I. Transvenous intracardiac echocardiography. Am J Cardiol 1981;47:1255–9.

41. Linzer M. The ultrasonic tissue characterization seminar: an assessment. J Clin Ultrasound 1976;4:97–102.

42. Rasmussen S, Corya BC, Feigenbaum H, Knoebel SB. Detection of myocardial scar tissue by M-mode echocardiography. Circulation 1978;57:230–7.

43. Martin RP, Rakowski H, French J, Popp RL. Idiopathic hypertrophic subaortic stenosis viewed by wide-angle, phased array echocardiography. Circulation 1979;59:1206–17.

44. Siqueira-Filho AG, Cunha CL, Tajik AJ, Seward JB, Schattenberg TT, Giuliani ER. M-mode and two-dimensional echocardiographic features in cardiac amyloidosis. Circulation 1981;63:188–96.

45. Wells PNT, Halliwell M. Speckle in ultrasonic imaging. Ultrasonics 1981;19:225–9.

46. Mimbs JW, O'Eonnell M, Bauwens D, Miller JW, Sobel BE. The dependence of ultrasonic attentuation and backscatter on collagen content in dog and rabbit hearts. Circ Res 1980;47:49–58.

47. Dines KA, Weyman AE, Franklin TD Jr, et al. Quantitation of changes in myocardial fiber bundle spacing with acute infarction, using pulse-echo ultrasound signals (abstr). Circulation 1979;60(suppl II):II-17.

48. Logan-Sinclair R, Wong CM, Gibson DG. Clinical application of amplitude processing of echocardiographic images. Br Heart J 1981;45:621–7.

49. Brinkley JF, Moritz WE, Baker DW. Ultrasonic three-dimensional imaging and volume from a series of arbitrary sector scans. Ultrasound Med Biol 1978;4:317–23.

50. Matsumoto M, Matsuo H, Kitabatake A, et al. Three-dimensional echocardiograms and two-dimensional echocardiographic images at desired planes by a computerized system. Ultrasound Med Biol 1977;3:163–70.

51. Ariet M, Geiser EA, Lupkeiwicz SM, Conetta DA, Christie LG, Conti CR. Advances in echocardiographic technology: three-dimensional reconstruction and computer analysis (abstr). Am J Cardiol 1982:49:896.

52. Pearlman AS, Stevenson JG, Baker DW. Doppler echocardiography: applications, limitations and future direction. Am J Cardiol 1980;46:1256–62.

53. Griffith JM, Henry WL. An ultrasound system for combined cardiac imaging and Doppler blood flow measurement in man. Circulation 1978;57:925–30.

54. Eyer MK, Brandestini MA, Phillips DJ, Baker DW. Color digital echo/Doppler image presentation. Ultrasound Med Biol 1981;7:21–31.

55. Stevenson G, Brandestini M, Weiler T, Howard A. Eyer M. Digital multigate Doppler with color echo and Doppler display-diagnosis of atrial and ventricular septal defects (abstr). Circulation 1979;60(suppl II):II-800.

56. Feigenbaum H, Stone JM, Lee DA, Nasser WK, Chang S. Identification of ultrasound echoes from the left ventricle using intracardiac injections of indocyanine green. Circulation 1970:41:615–21.

57. Seward JB, Tajik AJ, Hagler DJ, Ritter DG. Peripheral venous contrast echocardiography. Am J Cardiol 1977;39:202–12.

58. Lieppe W, Behar VS, Scallion R, Kisslo JA. Detection of tricuspid regurgitation with two-dimensional echocardiography and peripheral vein injections. Circulation 1978;47:128–32.

59. Weyman AE, Wann LS, Caldwell RL, Hurwitz RA, Dillon JC, Feigenbaum H. Negative contrast echocardiography: a new method for detecting left-to-right shunts. Circulation 1979;59:498–505.

60. Seward JB, Tajik AJ, Spangler JG, Ritter DG. Echocardiographic contrast studies: initial experience. Mayo Clin Proc 1975;50:163–72.

61. Bommer WJ, Mason DT, DeMaria AN. Studies in contrast echocardiography: development of new agents with superior reproducibility and transmission through lungs (abstr). Circulation 1979;60(suppl II):II-17.

62. Armstrong WF, Mueller TM, Kinney EL, Tickner EG, Dillon JC, Feigenbaum H. Assessment of myocardial perfusion abnormalities with contrast-enhanced two-dimensional echocardiography. Circulation 1982;66:166–73.

63. Wang X, Chiaen W, Hanjung C, Chengfa L, Yuchen H, Chungte T. Clinical application of cardiac contrast with hydrogen peroxide. Chin J Physiol 1979;1:2–9.

64. Gaffney FA, Lin J-C, Peshock RM, Buja LM. Hydrogen peroxide: a new, reliable 2D echocardiographic contrast agent (abstr). Am J Cardiol 1982;49:955.

65. Meltzer RS, Sartorius OE, Lancee CT, et al. Transmission of ultrasonic contrast through the lungs. Ultrasound Med Biol 1981;7:377–84.

66. Reale A, Pizzuto F, Gioffre PA, et al. Contrast echocardiography:transmission of echoes to the left heart across the pulmonary vascular bed. Eur Med J 1980;1:101–6.